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(54) POSITION CONTROL SYSTEM USING MAGNETIC FORCE

(71) We, HANDOTAI KENKYO SHINKOKAI a joint-stock company of Japan located at Kawauchi, Sendai-Shi, Miyagi-Ken, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a position control system and, more particularly, to a position control system using magnetic force.

Conventional position control for a controlled object is usually performed by screw mechanism. However, highly precise control cannot be performed by the screw control because of nonuniform friction between a male screw and a female screw, nonuniform pitch of the screw, and hysteresis of the screw etc. Accordingly, a conventional position control system cannot be applied to control a position of a controlled object, which must be controlled precisely, such as control of a mask of a photo-etching device or an evaporative deposition, by way of example. Moreover, two or three dimensional precision control is difficult by the conventional techniques.

An object of this invention is to provide a position control system capable of controlling a position of a controlled object precisely by the use of magnetic force.

Another object is to provide a position control system capable of controlling a position of a controlled object precisely in two or three dimensions.

Another object is to provide a position control system capable of automatically controlling the movement of a controlled object precisely to a desired position.

At least a part of a controlled object is composed of a magnetic substance. At least one pole of an electromagnet is opposed to the magnetic substance of the controlled object through an air gap therebetween so that a magnetic circuit including the magnetic substance, the air gap and the electromagnet is provided. Preset means is provided for presetting the width of the air gap more than a predetermined width when the control current is zero. Supporting means including at least one spring is provided for supporting the controlled object so as to be movable along a direction in which a magnetic force operates between the electromagnet and the magnetic substance. Control means coupled to the electromagnet is provided for controlling the control current of the electromagnet to adjust the magnetic force and also the width of the air gap so as to obtain a desired position of the controlled object along the above mentioned direction. The magnetic flux density of the magnetic circuit substantially saturates at a position where the air gap reaches a predetermined distance, while the elastic force of the spring is balanced with the magnetic force within the elastic region of the spring at the above-mentioned position to avoid mutual collision between the controlled object and the electromagnet. The above mentioned principle can be modified for performing two or three dimensional control and rotation control for a controlled object.

The principle, construction and operation of this invention will be better understood from the following detailed discussion taken in conjunction with the accompanying drawings, in which the same and equivalent parts are designated by the same reference numerals, characters and symbols, and in which:

Figures 1 and 2 are characteristic curves explanatory of the principle of this invention;

Figures 3A and 3B are side views explanatory of the principle of this invention;

Figures 4A and 4B are a plan view and a side view illustrating an embodiment of this invention;

Figure 5 is an elevation explanatory of another embodiment of this invention;

Figure 6 is a perspective view illustrating another embodiment of this invention in which two dimensional control is performed;

Figure 7 is a perspective view illustrating another embodiment of this invention in which two dimensional control is performed;

Figure 8 is a perspective view illustrating another embodiment of this invention in which two dimensional control is performed;

Figure 9 is a perspective view illustrating another embodiment of this invention in which one dimensional control along a vertical direction is performed;

Figure 10 is a perspective view illustrating another embodiment of this invention in which rotation control is performed;

Figure 11 is a perspective view illustrating another embodiment of this invention in which three dimensional control is performed;

Figures 12A and 12B are a plan view and a side view respectively, illustrating another embodiment of this invention in which coarse control and precise control are performed;

Figure 15 is a block diagram illustrating an embodiment of this invention in which automatic control is performed; and

Figures 13 and 14 are wave-forms explanatory of operations of the embodiment shown in Figure 15.

With reference to Figures 3A and 3B showing the construction of a system according to the invention, a controlled object 1 has a part 1*a* which is partially or entirely made of a magnetic substance. An electromagnet 2 comprising a U-shaped element made of a magnetic substance and a control winding 2*a*, has two magnetic poles, which are opposed to the magnetic part 1*a* of the control object through an air gap therebetween so that a magnetic circuit is provided including the magnetic part 1*a*, the air gap and the electromagnet 2. The electromagnet 2 is connected to a screw 8, which is coupled to a screwed supporter 5 fixed to a fixture 7. The screw 8 is so adjusted that the width of the air gap is more than a predetermined width L_0 when a control current of the electromagnet 2 is zero. A spring 4 fixed to a fixed object 6 is connected to the controlled object 1, so that the controlled object is movable along a direction in which a magnetic attractive or repulsive force functions between the electromagnet 2 and the magnetic part 1*a*. A current controller 3 supplies a control current to the winding 2*a* in response to a control signal from a terminal 9, so that the control current of the electromagnet 2 is controlled for adjusting the magnetic force and also the width of the air gap so as to obtain a desired position of the controlled object 1 along the above mentioned direction.

In this case, the magnetic flux density of the magnetic circuit substantially saturates as shown in Figure 1 at a condition where the air gap reaches a predetermined distance L_1 (as shown in Figure 3B), while the elastic force of the spring 4 is balanced with the magnetic force within the elastic range of the spring 4 at the above mentioned condition. As understood from Figure 1, the magnetic flux density increases along sections C_1, C_2, C_3 and C_4 of a magnetic characteristic curve. Accordingly, the magnetic force between the magnetic part 1*a* and the electromagnet 2 rapidly increases at the sections C_1 and C_2 but gradually increases at the sections C_3 and C_4. The gap between the magnetic part 1*a* and the electromagnet 2 can be precisely controlled by utilizing the gentle slope of the section C_4. Moreover, since the elastic force of the spring 4 is balanced with the magnetic force generated by the magnetic flux of the magnetic circuit corresponding to the section C_3 or C_4, collision between the controlled object 1 and the electromagnet 2 or between the controlled object 1 and the fixture 6 can be reliably avoided for both the attractive and the repulsive magnetic force.

To reduce control error, it is desirable that the magnetic substance of parts (1*a*, 2) of the magnetic circuit should not have a magnetic hysteresis characteristic (C_{12}–C_{13}–C_{14}–C_{15}–C_{16}–C_{17}) but a non-hysteresis characteristic (C_{11}, C_{18}), such as soft iron, as shown in Figure 2.

The two poles of the electromagnet 2 are opposed to the magnetic substance of part 1*a* in Figures 3A and 3B. Alternatively, one pole of a bar-shaped electromagnet may be opposed to the magnetic substance of part 1*a*. Other electromagnets, such as an E-shaped electromagnet, may be also employed as the electromagnet 2.

With reference to Figures 4A and 4B showing an embodiment of this invention, the controlled object 1 is supported by a pair of plate springs 4*a* and 4*b*, which are arranged parallel with each other and at right angles to the direction of motion of the controlled object in which a magnetic force functions between the electromagnet 2 and the magnetic substance of part 1*a*. One edge of each of the plate springs 4*a* and 4*b* is coupled to the controlled object 1 while the other edges of the plate springs 4*a* and 4*b* are fixed to a fixing plate 6*a* on a fixture 6. An interferometer 10 measures a position of the controlled object 1 in combination with a prism 10*a*, which is fixed to the controlled object 1. The function of current controller 3 is described with reference to Figures 3A and 3B.

The above mentioned electromagnet 2 may be further provided with at least one

pair of auxiliary magnetic poles 2–3 in addition to the usual magnetic poles 2–1 and 2–2 as shown in Figure 5. The auxiliary magnetic poles 2–3 are opposed to each other through an air gap having a magnetic resistance less than that of the air gap between the magnetic substance of part 1*a* and the magnetic poles 2–1 and 2–2 of the electromagnet 2. Accordingly, the magnetic flux of the magnetic circuit formed by the magnetic substance of part 1*a*, the air gap and the electromagnet 2 leaks through the auxiliary magnetic poles 2–3 before the magnetic flux density of the magnetic circuit reaches saturation. As a result of the above principle, the position of the controlled object 1*a* supported by two springs 4–1 and 4–2 is controlled in response to control of the control current of the winding 2*a* of the electromagnet 2 without collision between the controlled object 1 and electromagnet 2.

With reference to Figure 6, an embodiment of this invention is provided for performing two dimensional position control. In this embodiment, a second electromagnet 2–2 having a winding 2*a*–2 is provided in addition to a first electromagnet 2–1 having a winding 2*a*–1. The first electromagnet 2–1 controls the controlled object 1, which is supported on a supporting plate 6*a* by a pair of parallel plate springs 4*a* and 4*b*. The supporting plate 6*a* having a magnetic portion is attached to fixtures 6*b*–1 and 6*b*–2 by a pair of parallel plate springs 11*a* and 11*b*. The first direction of a first magnetic force acting between the first electromagnet 2–1 and the magnetic substance of the controlled object 1 intersects at right angles with the second direction of a second magnetic force acting between the second electromagnet 2–2 and the magnetic portion of the supporting plate 6*a*. The operation of this embodiment will be readily understood from the above mentioned principle, so that details are omitted.

With reference to Figure 7, another embodiment of this invention is provided for performing two dimensional position control. In this embodiment, two pairs of bar springs 4–1, 4–2, 4–3 and 4–4 are arranged parallel with one another and fixed on a fixing plate 6*a* so as to fixedly support a controlled object 1. A first electromagnet 2–1 and a second electromagnet 2–2 control independently the controlled object 1. Since the operations of this embodiment will be readily understood from the above mentioned principle, details are omitted.

With reference to Figure 8, another embodiment of this invention is provided for performing two dimensional position control. In this embodiment, two pairs of non-elastic ropes 12–1, 12–2, 12–3 and 12–4 connected to fixtures 6–3 are employed to hold four corners of a controlled object 1. Two coil springs 4–3 and 4–4 are respectively connected between a fixture 6–1 and the controlled object 1 and between a fixture 6–2 and the controlled object 1 so as to balance the magnetic forces of the first electromagnet 2–1 and the second electromagnet 2–2. Since operations of this embodiment can be readily understood from the above principle, details are omitted.

If a position of a controlled object 1 is controlled by electromagnet 2–3 in a vertical direction, the controlled object 1 is supported as shown in Figure 9 for example by a pair of parallel plate springs 13*a* and 13*b*, which are arranged perpendicularly to the vertical direction and fixed to a fixture 6*a*.

With reference to Figure 10, an embodiment of this invention is provided for performing rotational control of a controlled object 1. In this embodiment, the controlled object 1 is supported by a torsion spring 4–5, which is fixed between the controlled object 1 and a fixing plate 6*a*. An electromagnet 2–4 and an electromagnet 2–5 are provided to rotate the control object 1 with respect to the fixing point of the torsion spring 4–5. One of the electromagnets 2–4 and 2–5 may be eliminated, however two electromagnets 2–4 and 2–5 are desirable to perform rotation control without lateral shift of the position of the controlled object 1.

With reference to Figure 11, another embodiment of this invention is provided for performing three dimensional position control. This embodiment is substantially a combination of the embodiment shown in Figure 6 and the embodiment shown in Figure 9. In other words, supporting plates 6*b*–1 and 6*b*–2 are further supported by fixtures 6*c*–1 and 6*c*–2 through two pair of parallel spring plates (13*a*–1, 13*b*–1) and (13*a*–2, 13*b*–2) respectively. The electromagnets 2–2 and 2–3 are positioned so as to control the position of the supporting plate 6*a*. The three dimensional control is performed by independently controlling the three electromagnets 2–1, 2–2 and 2–3.

With reference to Figures 12A and 12B, another embodiment of this invention is provided for performing coarse position control and precise position control of a controlled object 1. In this embodiment, two pairs of slide bushes 15–1, 15–2 of a supporting plate 6*a* are slidably coupled to a pair of parallel sliding guides 17*a* and 17*b*, which are supported by supporting bases 16–1, 16–2, 16–3 and 16–4. A screwed nut 5*a* connected to the supporting plate 6*a* is coupled to a driving screw 8, which is driven by a motor 29. If the motor 29 is driven by a control current from a controller 3, the position of the controlled object 1 is controlled in a coarse manner while precise position control is performed

by the control of the electromagnet 2 on the supporting plate 6 as described above. The controller 3 is controlled by the output of a speed detector 30 as mentioned below.

With reference to Figure 15, another embodiment of this invention is provided for automatically performing the position control of a controlled object 1, which is supported by a supporting plate 6*a* through a pair of plate springs 4*a* and 4*b*. An input digital value representative of the desired position of the controlled object is preset through an input terminal 20 to a register 21. An interferometer 32 detects a position of the controlled object 1 with respect to a reference position. A detected output of the interferometer 32 is applied to a converter 33, in which the detected output is converted to pulses. The number of pulses represents a level of the detected output of the interferometer 32. A counter 34 is a reversible counter, which counts the output pulses of the converter 33 with reference to the polarity of the detected output of the interferometer 32. The counting state of the counter 34 is thus increased when the polarity of the output of the interferometer 32 is positive and is reduced when the polarity of the ouput of the interferometer is negative. The counting state of the counter 34 is then stored in a register 35. A comparator 22 compares contents of the registers 21 and 35, so that an input digital value indicative of a difference between contents of the registers 21 and 35 is applied to a distributor 23. The most significant digits of the control code control a stepping motor 29 through a motor control 28 to perform coarse control of the supporting plate 6*a*. The least significant digit of the control code in converted to an analogue control signal at a D–A converter 24 when the most significant digits become zero as mentioned below. The analogue control signal is applied, through a PID control 25 and a dc amplifier 26, to an electromagnet 27 to perform precise position control of a controlled object 1. A speed detector 30 detects a travelling speed of the controlled object 1 and controls the PID control 25 through a logic circuit 31 to damp the index of the PID control 25 so as to accelerate establishing of the controlled object 1 in a controlled position. In other words, a feedback loop comprising elements 1, 30, 31, 25, 26 and 27 operate as an electrical damper for damping any hunting movement of the object 1.

As a result of the above construction, the position of the supporting plate 6*a* is at first controlled by the most significant digits of the control code from the comparator 22. After the most significant digits of the control code assume zero, the least significant digit of the control code controls the PID control 25 so that the least significant digit is reduced to zero as shown in Figure 13 by arrows. In response to the application of the least significant digit to the PID control 25, the position of the controlled object 1 is controlled on the supporting plate 6*a* for a desired deviation D_0 of the object 1 as shown in Figure 14, on which a short period during which oscillation occurs is enlarged for the purposes of illustration. Accordingly, the position of the controlled object 1 is automatically controlled to a desired position indicated by the control code unit from the terminal 20.

The above mentioned automatic control can be also applied to the above mentioned two and three dimensional control and rotational control.

Moreover, many other combination of control, such as a combination of one dimensional control and rotational control, can be provided in accordance with this invention.

Furthermore, if an auxiliary electromagnet is provided for each of the above mentioned electromagnets so that one is controlled in a rapidly changed section C_1 or C_2 and the other is controlled in a gentle section C_3 or C_4 in a characteristic curve as shown in Figure 1, coarse control can be also carried out by an electromagnet in exchange for screw control in the embodiment shown in Figures 12A, 12B and 15.

WHAT WE CLAIM IS:—

1. A position control system using magnetic force, for controlling the position of an object, at least a part of which is composed of a magnetic substance; comprising

an electromagnet, at least one pole of which is opposed to the magnetic substance of said controlled object through an air gap therebetween so that a magnetic circuit including the magnetic substance, the air gap and the electromagnet is provided, the magnetic flux density of the magnetic circuit being controlled by a control current of the first electromagnet;

preset means for presetting the width of the air gap more than a predetermined width when the control current is zero,

supporting means including at least one spring for supporting said controlled object so as to be movable along a direction in which a magnetic force operates between the electromagnet and the magnetic substance; and

control means coupled to said electromagnet for controlling the control current of said electromagnet to adjust said magnetic force and also the width of said air gap so as to obtain a desired position of said controlled object along said direction, the magnetic flux density of said magnetic circuit reaching a substantially saturated value at a position where said air gap reaches a pre-

determined distance, the elastic force of said spring being balanced with said magnetic force within the elastic region of the spring at said position.

2. A position control system according to claim 1, in which the electromagnet has a plurality of poles arranged in a line and comprises a U-shaped element made of a magnetic substance having no magnetic hysteresis and a control coil wound on the U-shaped element, two poles of the U-shaped element being opposed to said magnetic substance of the controlled object through said air gap.

3. A position control system according to claim 2, in which the electromagnet has at least one pair of auxiliary magnetic poles, which are opposed to each other through an additional air gap having a magnetic resistance less than that of said air gap between the magnetic substance and the electromagnet, thereby leaking the magnetic flux of said magnetic circuit through the auxiliary magnetic poles before the magnetic circuit completely saturates.

4. A position control system according to claim 1, in which said supporting means comprises a pair of plate springs arranged parallel to each other and at right angles with said movable direction, and in which each one edge of said plate springs is coupled to said controlled object while each of the other edge of said plate springs is fixed to a fixing base.

5. A position control system according to claim 1, further comprising, measuring means for measuring a distance of said controlled object from a reference position, conversion means coupled to said measuring means for converting said measured distance to a digital value, input means for temporarily storing an input digital value representative of said desired position of said controlled object, a comparator coupled to said conversion means and said input means for producing a difference between said controlled digital value and said input digital value, means coupled to said comparator and said control means for controlling said control current in response to said difference so as to reduce the difference.

6. A position control system using magnetic force according to claim 1, further comprising:

a second electromagnet, at least one pole of which is opposed to the magnetic substance of said controlled object through a second air gap therebetween so that a second magnetic circuit including the magnetic substance, the second air gap and the second electromagnet is provided, the magnetic flux density of the second magnetic circuit being controlled by the control current of the second electromagnet;

second presetting means for presetting the width of the second air gap more than a second predetermined width when the control current of the second electromagnet is zero;

and in which said supporting means is also capable of movement in the direction in which the second magnetic force operates and is provided with at least two springs for supporting said controlled object so as to be movable along a plane in which a first direction of a first magnetic force acting between the first electromagnet and the magnetic substance intersects at right angles with a direction of a second magnetic force acting between the second electromagnet and the magnetic substance;

second control means being coupled to said second electromagnet for controlling the control current of said second electromagnet to adjust said second magnetic force and also the width of said second air gap so as to obtain a desired position of said controlled object along said second direction, the magnetic flux density of said second magnetic circuit reaching a substantially saturated value at a second position where said second air gap reaches a predetermined second distance, the elastic force of the other of said two springs being balanced with the second magnetic force within the elastic region of the other spring at said second position.

7. A position control system according to claim 6, in which each of said electromagnets has a plurality of poles arranged in a line and comprises a U-shaped element made of a magnetic substance having no magnetic hysteresis and a control coil wound on the U-shaped element, two poles of the U-shaped element being opposed to said magnetic substance of the controlled object through said first or second air gap.

8. A position control system according to claim 7, in which each electromagnet has at least one pair of auxiliary magnetic poles, which are opposed to each other through an additional air gap having a magnetic resistance less than either of said first and second air gaps, thereby leaking the magnetic flux of either of said first magnetic circuit and second magnetic circuits through the auxiliary magnetic poles before said magnetic circuit completely saturates.

9. A position control system according to claim 6, in which said supporting means comprises two pairs of plate springs, one pair of plate springs being arranged parallel to each other and at right angles with said first direction, the other pair of plate springs being arranged parallel to each other and at right angles with said second direction; in which each one edge of said one pair of plate springs is coupled to said controlled object while each other edge of said one pair of plate springs is coupled to a movable supporting plate; and in which each one edge

of said other pair of plate springs is coupled to said movable supporting plate while each said other edge of said other pair of plate springs is fixed to a fixing base.

10. A position control system according to claim 6, in which said supporting means comprises two pairs of bar springs arranged parallel to each other, one end of each of said bar springs being coupled to said controlled object, the other end of each of said bar springs being fixed to a fixing base.

11. A position control system according to claim 6, in which said supporting means comprises two pairs of non-elastic ropes and two coil springs, respective one ends of said ropes being connected to a fixing base while the respective other ends of said ropes are connected to four connection points on said controlled object, one of said two coil springs being connected between said controlled object and a fixing base so as to act in the first direction, the other of said two coil springs being connected between said controlled object and a fixing base so as to act in the second direction.

12. A position control system according to claim 6, further comprising for each electromagnet, measuring means for measuring the distance of said controlled object from a reference position, conversion means coupled to said measuring means for converting said measured distance to a digital value, input means for temporarily storing an input digital value representative of said desired position of said controlled object, a comparator coupled to said conversion means and said input means for producing a difference between said controlled digital value and said input digital value, means coupled to said comparator and a corresponding one of said control means for controlling said control means for controlling said control current in response to said difference so as to reduce the difference.

13. A position control system using magnetic force according to claim 1, further comprising:

a second electromagnet, at least one pole of which is opposed to the magnetic substance of said controlled object through a second air gap therebetween so that a second magnetic circuit including the magnetic substance, the second air gap and the second electromagnet is provided, the magnetic flux density of the second magnetic circuit being controlled by the control current of the second electromagnet;

a third electromagnet, at least one pole of which is opposed to the magnetic substance of said controlled object through a third air gap therebetween so that a third magnetic circuit including the magnetic substance, the third air gap and the third electromagnet is provided, the magnetic flux density of the third magnetic circuit being controlled by the control current of the third electromagnet;

second presetting means for presetting the width of the second air gap more than a second predetermined width when the second control current of the second electromagnet is zero; and

third presetting means for presetting the width of the third air gap more than a third predetermined width when the third control current of the third electromagnet is zero;

and in which said supporting means is provided with at least three springs for supporting said controlled object so as to be movable in a three dimensional manner in which a first direction of a first magnetic force acting between the first electromagnet and the magnetic substance, a second direction of a second magnetic force acting between the second electromagnet and the magnetic substance, and a third direction of a third magnetic force acting between the third electromagnet and the magnetic substance intersect at right angles with one another;

second control means being coupled to said second electromagnet for controlling the control current of said second electromagnet to adjust said second magnetic force and also the width of said second air gap so as to obtain a desired position of said controlled object along said second direction, the magnetic flux density of said second magnetic circuit reaching a substantially saturated value at a second position where said second air gap reaches a predetermined second distance, the elastic force of second one of said three springs being balanced with said second magnetic force within the elastic region of the spring at said second position;

third control means being coupled to said third electromagnet for controlling the control current of said third electromagnet to adjust said third magnetic force and also the width of said third air gap so as to obtain a desired position of said controlled object along said third direction, the magnetic flux density of said third magnetic circuit reaching a substantially saturated value at a third position where said third air gap reaches a predetermined third distance, the elastic force of said three springs being balanced with said third magnetic force within the elastic region of the spring at said third position.

14. A position control system according to claim 13, in which each of said electromagnets, has a plurality of poles arranged in a line and comprises a U-shaped element made of a magnetic substance having no magnetic hysteresis and a control coil wound on the U-shaped element, two poles of the U-shaped element being opposed to said magnetic substance of the controlled object through a corresponding one of said first, second and third air gaps.

15. A position control system according to claim 14, in which each electromagnet has at least one pair of auxiliary magnetic poles, which are opposed to each other through an additional air gap having a magnetic resistance less than either of said first and second air gaps, thereby leaking the magnetic flux of either of said first magnetic circuit, said second magnetic circuit or said third magnetic circuit through the auxiliary magnetic poles before the said magnetic circuit completely saturates.

16. A position control system according to claim 13, in which said supporting means comprises three pairs of plate springs, the first pair of plate springs being arranged parallel to each other and at right angles with said first direction, the second pair of plate springs being arranged parallel to each other and at right angles with said second direction, the third pair of plate springs being arranged parallel to each other and at right angles with said third direction; in which each one edge of said first pair of plate springs is coupled to said controlled object while each other edge of said first pair of plate springs is coupled to a first movable supporting plate; in which each one edge of said second pair of plate springs is coupled to said first movable supporting plate while each other edge of said second pair of plate springs is coupled to a pair of second movable supporting plates; and in which each one edge of said third pair of plate springs is coupled to said second movable supporting plate while each other edge of said third pair of plate springs is fixed to at least one fixing base.

17. A position control system according to claim 13, further comprising for each of said first, second and third electromagnets measuring means for measuring the distance of said controlled object from a reference position, conversion means coupled to said measuring means for converting said measured distance to a digital value, input means for temporarily storing an input digital value representative of said desired position of said controlled object, a comparator coupled to said conversion means and said input means for producing a difference between said controlled digital value and said input digital value, means coupled to said comparator and a corresponding one of said control means for controlling said control means for controlling said control current in response to said difference so as to reduce the difference.

18. A position control system using magnetic force, according to claim 1, in which

said supporting means comprises a torsion spring for supporting said controlled object so as to be rotatable with respect to the axis of said torsion spring in a rotational direction in which a magnetic force functions between the electromagnet and the magnetic substance; and

said control means is coupled to said electromagnet for controlling the control current of said electromagnet to adjust said magnetic force so as to obtain a desired position of said controlled object along said rotational direction, the magnetic flux density of said magnetic circuit reaching a substantially saturated value when said air gap reaches a predetermined distance, a torsional stress of said torsion spring being balanced with said magnetic force within the elastic region of the spring.

19. A position control system according to claim 18, in which the electromagnet has two poles arranged in a line and comprises a U-shaped element made of a magnetic substance having no magnetic hysteresis and a control coil wound on the U-shaped element, two poles of the U-shaped element being opposed to said magnetic substance of the controlled object through said air gap.

20. A position control system according to claim 19, in which the electromagnet has at least one pair of auxiliary magnetic poles, which are opposed to each other through an additional air gap having a magnetic resistance less than that of said air gap, thereby leaking the magnetic flux of said magnetic circuit through said auxiliary magnetic poles before the magnetic circuit completely saturates.

21. A position control system according to claim 18, further comprising, measuring means for measuring the distance of said controlled object from a reference position, conversion means coupled to said measuring means for converting said measured distance to a digital value, input means for temporarily storing an input digital value representative of said desired position of said controlled object, a comparator coupled to said conversion means and said input means for producing a difference between said controlled digital value and said input digital value, means coupled to said comparator and said control means for controlling said control means for controlling said control current in response to said difference so as to reduce the difference.

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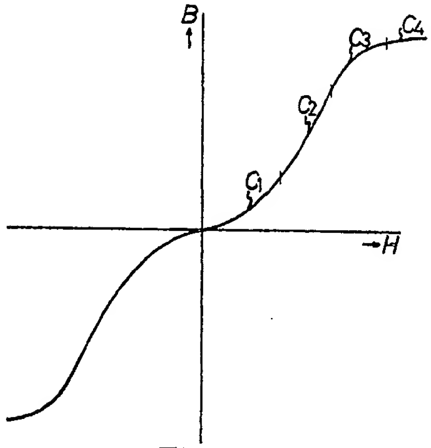

Fig. 1

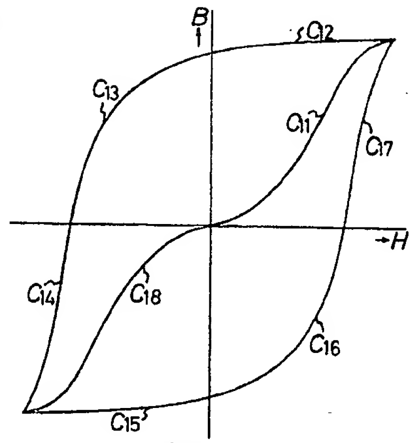

Fig. 2

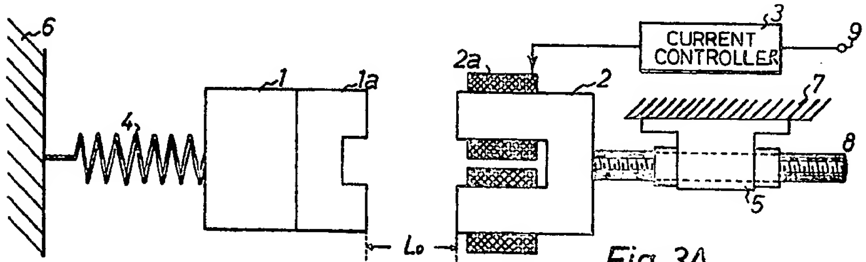

Fig. 3A

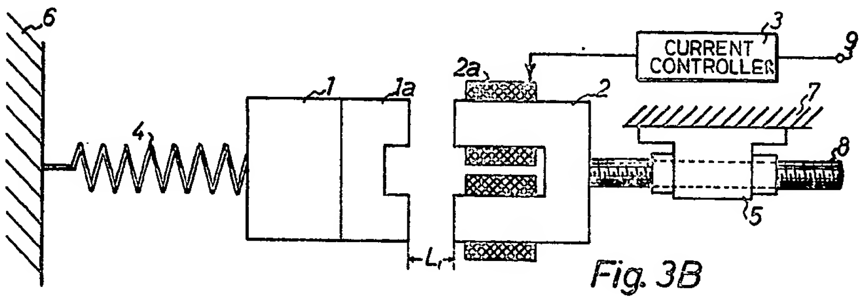

Fig. 3B

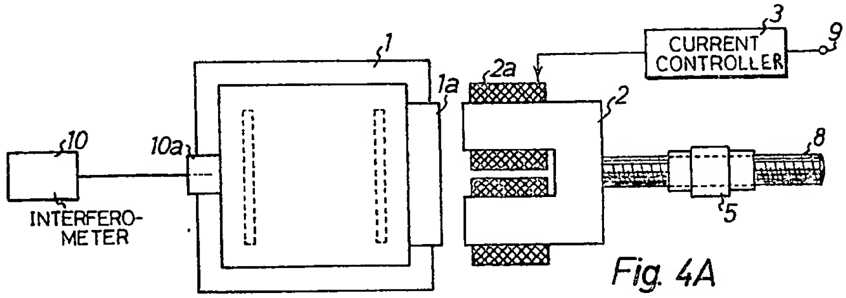

Fig. 4A

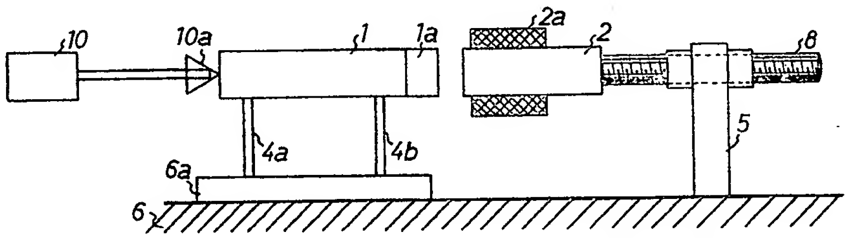

Fig. 4B

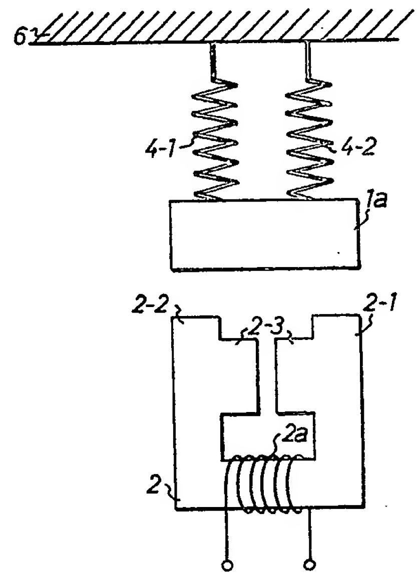

Fig. 5

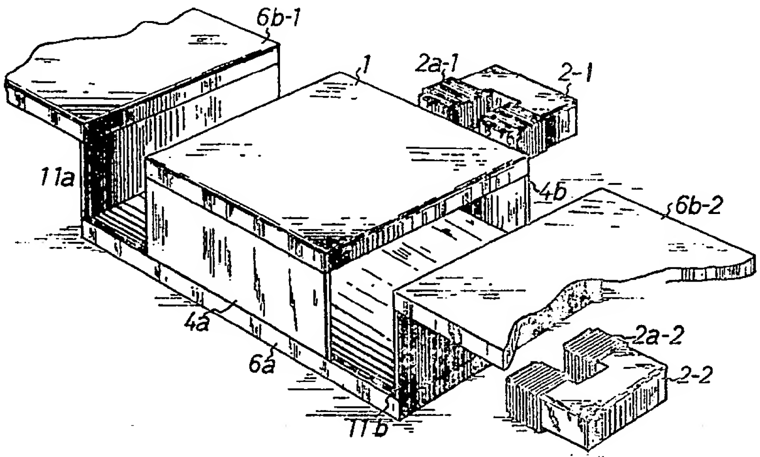

Fig. 6

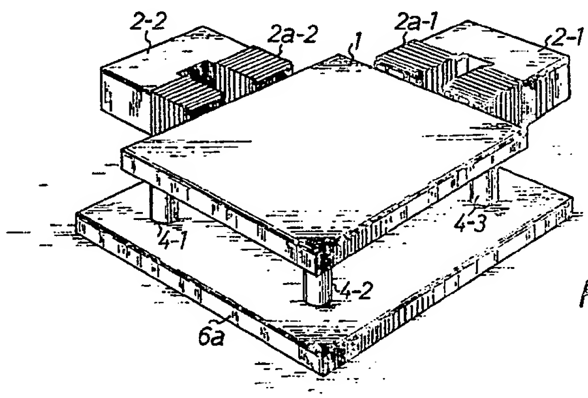

Fig. 7

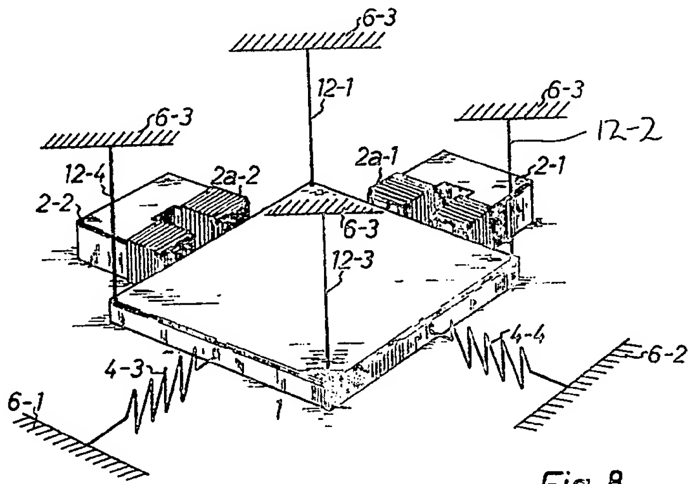
6-3
12-1
6-3
12-2
6-3
12-4
2a-2
2a-1
2-1
2-2
6-3
12-3
4-4
6-2
4-3
6-1
1

Fig. 8

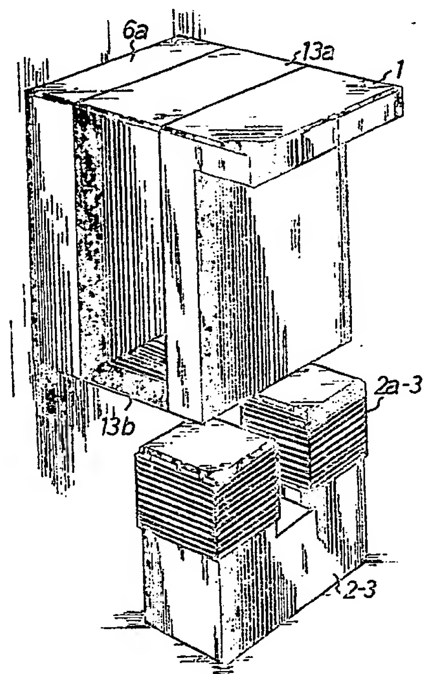
6a
13a
1
2a-3
13b
2-3

Fig. 9

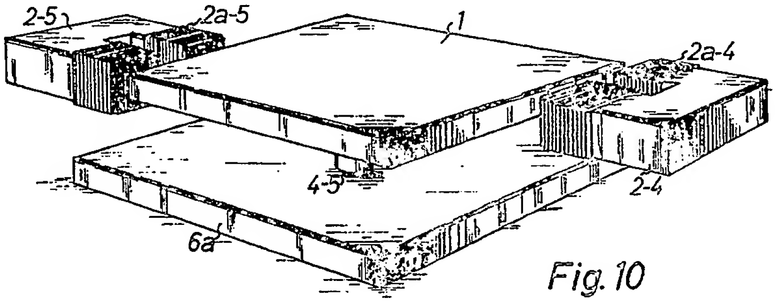
2-5
2a-5
1
2a-4
4-5
2-4
6a

Fig. 10

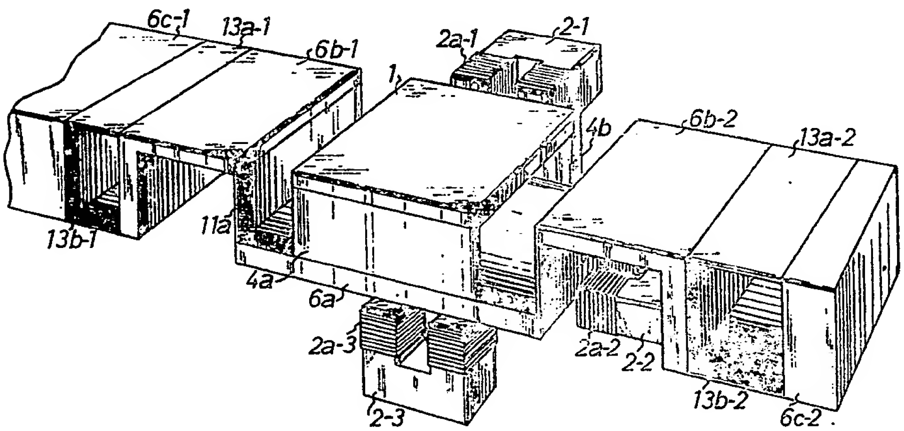
6c-1
13a-1
6b-1
2a-1
2-1
1
4b
6b-2
13a-2
11a
13b-1
4a
6a
2a-3
2a-2
2-2
13b-2
6c-2
2-3

Fig. 11

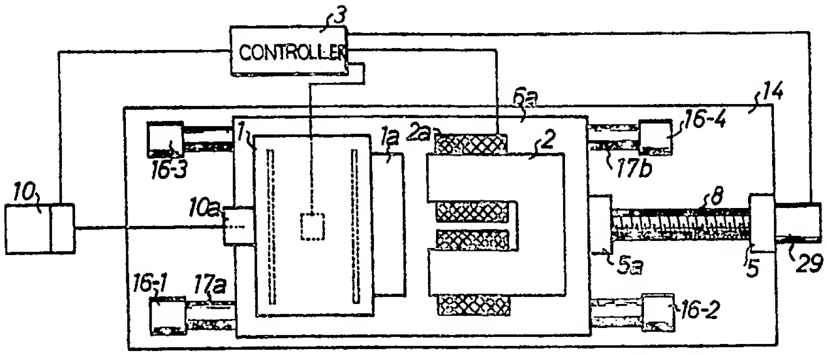

Fig. 12A

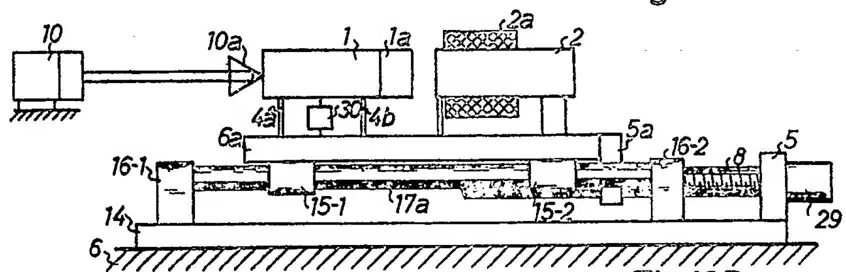

Fig.12B

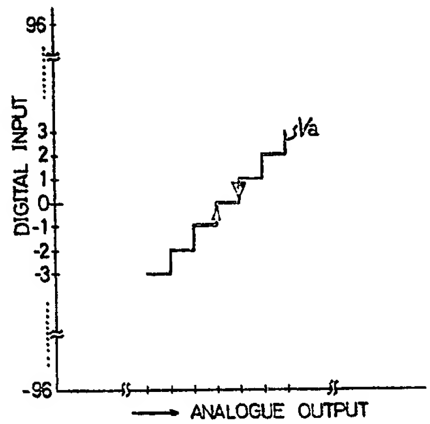

Fig. 13

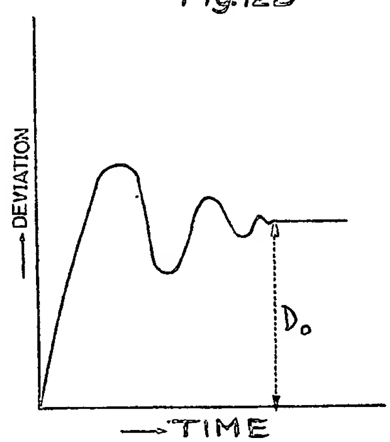

Fig. 14

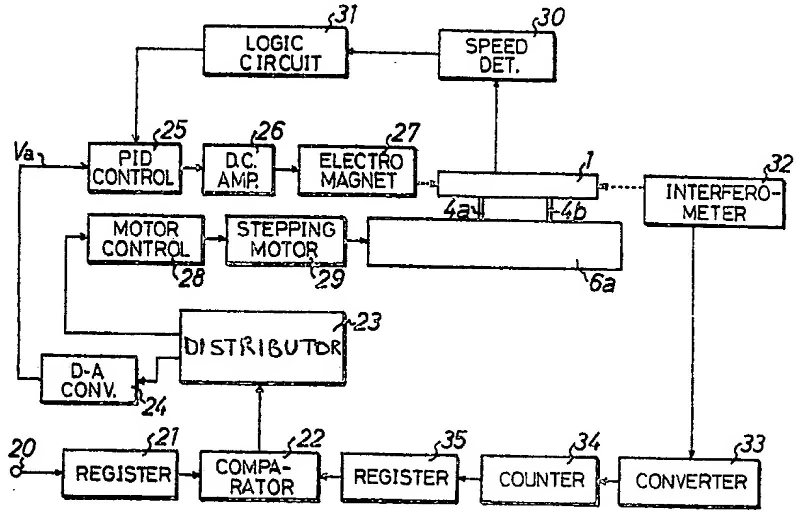
LOGIC CIRCUIT
31
SPEED DET.
30
Va
PID CONTROL
25
D.C. AMP.
26
ELECTRO MAGNET
27
1
INTERFERO-METER
32
4a
4b
MOTOR CONTROL
28
STEPPING MOTOR
29
6a
DISTRIBUTOR
23
D-A CONV.
24
20
REGISTER
21
COMPA-RATOR
22
REGISTER
35
COUNTER
34
CONVERTER
33

Fig. 15